Technical Review of Irrigation Water Use Efficiency and Efficiency Comparison Within WIP

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A technical review of irrigation water use efficiency was conducted for purposes of demonstrating the various bases for defining irrigation efficiency. This was accomplished by reviewing definitions offered by various experts in the field of irrigation practice, including definitions developed by the State of California's Department of Water Resources (CDWR). Additionally, specific examples of estimated irrigation water use and efficiency are presented for selected projects.

Generally speaking, the principal and presently recognized expressions of irrigation related efficiency can be expressed in terms of the irrigation project unit (Overall Project Irrigation Efficiency), or in terms of its parts such as the conveyance, distribution and farm unit, or On-Farm portions.

- Overall Irrigation Efficiency is the amount of water used for all beneficial irrigation uses within the project divided by the total water diverted to the project.
- Conveyance and Distribution Efficiency is the water delivered to farm headgates divided by total project diversions.
- On-Farm Irrigation Efficiency is the amount of water used beneficially within the farm unit divided by the farm headgate deliveries.

Much of the controversy surrounding the definition of irrigation efficiency involves the definition of beneficial use and the treatment of return flow in the calculation of efficiency. Obviously, there would be few disputes regarding water use by an irrigation project, if all parties agreed on estimates of water quantities involved, that the quantities used are used beneficially and that unused water is available for use by other parties. The California Water Update, Bulletin 160-98 states that "It is assumed that by 2020 SAE will reach 73 percent in all regions of California, averaged across crop types, farmland characteristics, and management practices.

Israelsen, 1950

The relevance of irrigation efficiency was beginning to receive close attention in the United States following World War II. Some of the authors who originally discussed this topic are: Israelsen, 1950; Hansen, 1957; and Willardson, 1959.

Iraelsen's (1950) definition of irrigation efficiency (I_e) identifies only the water "evaporated" (evapotranspired) by crops in his definition of irrigation efficiency, where:

$$I_e = \frac{\text{Irrigation Water Evaporated by Crops}}{\text{Water Delivered or Applied}}$$

Hansen, 1957

In order to account for aspects of irrigation water use beyond the amount evapotranspired by crops, Dr. Hansen proposed additional terms for inclusion in assessments of irrigation efficiency. These are "water storage efficiency," which focuses on the storage of water within the crop root zone and therefore the adequacy of irrigation water application and the term "water distribution efficiency," in order to account for the fact that irrigation water applied to a field cannot be applied with perfect uniformity.

Willardson, 1959

Willardson made the observation that "Economic competition daily reduces the supply of water available for agriculture. It also is reducing the profit margin on farms and requiring more efficient crop production through better farming methods, including better irrigation." In providing a historical perspective to the development of irrigation efficiency, Willardson used the early concept of Water Duty. He states "The concept of the relation of irrigation water used to land area served, or the idea of 'irrigation efficiency' has evolved as a matter of necessity." An early expression of the concept was the term, "duty of water", mentioned by Dr. J. A. Widstoe in 1914. This term "duty of water" was used as a measure of the area of land that would be served by a given unit of water. It is a useful term and might better be spoken of as, "water allotment." It defines the amount of water that must be provided to an area to meet the consumptive use needs of the crops and to provide the extra water which will be needed for leaching or which will be lost in canals and farms due to local peculiarities of soil, water, and irrigation practice. It is an expression of the practical water needs of the land.

Willardson identified 13 relationships which reflect the various "phases" of water within an irrigation project for purposes of separating levels at which irrigation efficiency can be expressed. These terms are included here directly from his 1959 paper presented to the American Society of Agricultural Engineers (ASAE).

1. Project Water Use Efficiency is the ratio of the water beneficially consumed within a project to the water diverted into the project. This term will tell what proportion of the water diverted was used to produce crops in the project. Salt concentration, which renders water unusable, as does consumptive use, might be considered consumptive if the necessary amount is known with some precision. The water which passes beyond the confines of the project may not be lost to humanity, but is beyond recovery for the project.

2. Farm Water Use Efficiency is the ratio of the water beneficially consumed on a farm to the water delivered to the farm. Water which evaporates from depressions or is used by non-economic or non-aesthetic vegetation cannot be considered as being beneficially consumed. It is possible to retain 100 percent of the water delivered within the farm boundary and still have a low farm water use efficiency if the water is consumed by non-economic vegetation. Where leaching is required to maintain a favorable salt balance in the soil, the farm water use efficiency might include sufficient water to remove the salt at wilting point concentrations. The full volume of deep percolation losses can seldom be considered beneficial consumption. Even though the word efficiency has been used, it does not mean that 100 percent is the practical value to be reached in

every case. Economic factors, particularly involving labor, may dictate rather low efficiencies but they should be low by conscious design, not negligence.

3. Field Water Use Efficiency is the ratio of water beneficially consumed by the crop to the water delivered to the field.

4. Water Conveyance Efficiency is the ratio of water delivered to the water placed in a canal or other conveyance.

5. Farm Water Application Efficiency is the ratio of the water stored in the various plant root depths on the farm to the amount of water delivered to the farm.

6. Field Water Application Efficiency is the ratio of water stored in the root depth soil of a field to the water delivered to the field.

7. Water Storage Factor is the ratio of the water stored in the root depth by irrigation to the water needed in the root depth to bring it to field capacity.

8. Moisture Storage Capacity Factor is the ratio of the average available moisture contained in the plant root depth at the time of sampling to the average available moisture capacity of that held in the soil and is particularly useful in humid areas and in dry farming operations.

9. Water Distribution Factor is a term for evaluating the uniformity of irrigation water distribution in a field. The factor is equal to 1 minus the ratio of the average numerical deviation of the water absorbed by the soil at each sampling point from the average absorbed, to the average water absorbed by the soil.

10. Moisture Distribution Factor is a term similar to the water distribution factor mentioned above. It is the difference between 1 and the ratio of the average

numerical deviation of moisture in each sample from the average amount of moisture in the root depth.

11. Transpiration Factor is the ratio of the amount of moisture transpired by the crop to the amount of water consumptively used by the crop.

12. Irrigation Adequacy is a combination of terms. The values of moisture distribution factor and moisture storage capacity factor can be examined conjointly. An irrigation, to be adequate, should fill the root zone uniformly to field capacity. If the moisture in the field is distributed uniformly, but the full capacity of the soil to store moisture has not been used, the true adequacy of the irrigation will be apparent. A high field water application efficiency may be obtained when an insufficient amount of irrigation water is poorly distributed, the irrigation will not be adequate.

13. Efficiency of Irrigation as a specific term may be examined at the field level by a combination of three terms: moisture distribution factor, moisture storage capacity factor, and field water application efficiency.

Willardson summarizes his treatment of irrigation efficiency by stating: "There is nothing in the above proposals to indicate that the proper or ultimately expected value for any of the terms will be 1 or 100 percent. The governing effects of economics and the characteristics of the soils, waters, and crops will dictate the desirable value in each case."

Burt, 1990

Dr. Charles Burt addressed the definition of irrigation efficiency as a matter of reconciling variations in terminology and offered the following definition, which he points out was accepted by the CDWR Office of Water Conservation and conforms to definitions established by the American Society of Civil Engineers, Irrigation and Drainage Division.

$$\text{Irrigation Efficiency} = \frac{\text{Irrigation Water Beneficially Used}}{\text{Irrigation Water Applied}} \times 100$$

Burt made a special note to distinguish this definition as different from "Water Application Efficiency" or "Irrigation Water Application Efficiency."

Corollary to irrigation efficiency, Burt defined a term for irrigation distribution uniformity, that was adopted by CDWR. "The "Distribution Uniformity" describes how evenly water is made available to plants throughout a field. Distribution Uniformity (DU) is defined as:

$$\text{Distribution Uniformity} = \frac{\text{Minimum Depth Infiltrated}}{\text{Average Depth Infiltrated}} \times 100$$

Burt contrasts the above definition with Christiansen's Coefficient of Uniformity which produces a higher uniformity number using the same data. He states that Christiansen's Coefficient of Uniformity and others like it are "used only to describe one of the many uniformity components which must be combined to give a field DU." Rules cited by Burt, regarding DU, include:

- If there is "perfect timing," and no losses due to runoff or evaporation, then irrigation efficiency = distribution uniformity. (This is not a real world case)

- If the whole field is under-irrigated, then beneficial use = average depth infiltrated. (This case is encountered in the real world and is one reason for high irrigation efficiencies, although crop yields and long-term salinity control within fields are compromised)

Burt notes that "Ideally, irrigation methods should apply water uniformly to each plant in a field. Such a method would have a DU of 100%. In fact, no system is capable of applying water so that every plant in a field receives the same amount of water. For all methods, some points in the field are always over and/or under-irrigated. A low DU results in water and energy wastage because excess water must be pumped onto a field to apply enough water at the dry points." Burt clarifies DU by stating that "DU is Not a Measure of Efficiency, because it does not quantify beneficial use or even deal with non-infiltrated water. However, a high irrigation efficiency with a fully irrigated field is only possible if there is a high DU." Burt goes on to note that irrigation efficiency can only be higher than the DU if there is <u>under-irrigation.</u>

With regard to field runoff, Burt states "Runoff (tailwater) with surface irrigation systems does NOT decrease efficiencies if it is collected for reuse later somewhere on the farm. Runoff does not have to be recycled on the same field or irrigation set in order to qualify as "beneficial use." He also states that "Runoff (which is collected) is a sign of good management in arid areas, because the existence of tailwater indicates a good advance ratio and good DU."

The point that more water is required for the irrigation of a field than the amount of water necessary to meet consumptive use of crops, leaching requirements, and other beneficial uses cannot be over emphasized. The fact that extra water is required above and beyond beneficial uses is important to note, as this extra amount of water is not, within strict engineering definitions, considered beneficial use. Obviously, some extra amount of water is however necessary for beneficial uses to take place. The matter of who is responsible for its availability and reuse is a matter of debate.

<u>Summary of Keller and Keller 1995</u>

Keller and Keller (1995) compared the "Classical" definition of efficiency (Israelsen, 1950) with that of Effective Irrigation Efficiency (Jensen, 1980) and Effective Irrigation Efficiency subject to leaching requirements (Keller and Keller, 1995). A review of these definitions is instructive with regard to Imperial Irrigation District (IID) for several reasons. One good reason is that Keller and Keller use IID as a case example which directs our attention to the fact that IID, unlike other lower Colorado River projects, is not situated within the river supply system so as to easily benefit from the inclusion of return flow into expressions of irrigation efficiency, as might be done for upstream projects adjacent to the River. Inclusion of return flow (from deep percolation or field surface runoff) in the assessment of an irrigation district is particularly useful when assessing the combined effects of all users within a basin since the return and reuse of unused portions of diverted water has the effect of increasing basin wide efficiency. Keller and Keller use the Nile River Basin as an example of an irrigation project which is comprised of many, relatively low efficiency irrigators who reuse water successively as it moves down-gradient within the system. The cyclical reuse of inefficiently used water has the net effect of producing relatively good basin wide efficiencies. The reuse of such water and the net effect of increasing basin wide irrigation efficiency, in this way, is termed the "multiplier effect" by Keller et al. (1990).

Inconsistent inclusion of return flow or "multiplier effects," in the assessment of project specific irrigation efficiency is however a major concern when considering irrigation efficiency for the purposes of comparing various irrigation districts, since it can confuse inefficient irrigation practices with efficient ones. The U.S. Bureau of Reclamation (BOR) should acknowledge the distinction before passing judgment regarding water allocation reduction to IID and perhaps scrutinize other lower Colorado River diverters. The fact that IID does not generate return flow to the Colorado River cannot therefore be used as a basis to suggest that IID's conveyance, distribution, and on-farm efficiencies are substandard. Even without inclusion of return flow, IID's project efficiencies are in fact quite high, as evidenced by a number of determinations including those made by Keller and Keller (1995), who calculated IID's overall efficiency at 71.9 percent prior to conservation efforts. They also estimated an overall efficiency of 74.6 percent for the project following anticipated conservation improvements, some of which have since been implemented.

Definitions of irrigation efficiency pointed out by Keller and Keller (1995) include:

Iraelsen's (1950) definition of irrigation efficiency, where:

$$I_e = \frac{\text{Irrigation Water Evaporated by Crops}}{\text{Water Delivered or Applied}}$$

Jensen's definition (1977), which does not account for leaching requirements or salt buildup in return flows, defines net irrigation efficiency (E_n) as:

$$E_n = I_e + E_r(1 - I_e)$$

where:

- E_r = the fraction of water that is not evaporated and can be recovered.

Keller and Keller (1995) point out that "Jensen aptly points out that the classical efficiency concept is commonly misapplied in resource development because the recovery of irrigation water is ignored. In order to overcome the absence of a leaching water term and to address differences between project specific and regional water use efficiency concerns, Keller and Keller make use of the previous relationships and proposed the following modified regional efficiency equation:

$$E_e = U_{ci}/U_e = U_{ci}/(V_{eI} - V_{eO}) = \frac{\text{CropET} - \text{Effective Precipitation}}{(1\text{-}LR_I) \times V_I - (1 - LR_O) \times V_O}$$

where:

- E_e is the Effective Irrigation Efficiency
- U_{ci} is the Crop Consumptive Use of Applied Irrigation Water and U_e is the Effective Use
- V_{eI} and V_{eO} are the effective inflow and outflow and V_I and V_O are total inflow and outflow
- LR_I and LR_O represent the leaching fraction as input and output respectively

Keller and Keller (1995) suggest the derived relationship is "the efficiency of an irrigation system expressed in terms of the amount of water consumed by the system."

Terminal Users Within a Basin

Again, the importance of macro level assessments of irrigation efficiency address return flow, since return flow back to the source stream represents water available to other users. These are used to create the understanding that when return flows are generated and available to other downstream users, the efficiency of the whole system is greater than that of individual projects because of the "Multiplier Effect." Stated in another way, the inefficiencies of upstream users represent part of the water supply to the next downstream user and so on. A point needs to be made here with that being that somewhere within a chain of projects, such as those along the Colorado River, there are end-system projects. For the lower Colorado River, this end is represented by IID, Coachella Valley Water District (CVWD) and Mexico, who are the terminal users of Colorado River Water. These entities receive their water after it has been subject to the multiplier effect. A multiplier effect could take place and enhance the lower Colorado River system's overall efficiency further if Coachella and IID did not represent transbasin diversions from the River. As such, Mexico does not have an opportunity to reuse water from these districts. Additionally, other users within California have not elected to reuse water from these districts.

Being the terminal user within a basin has its drawbacks since tail-end users not only receive water of degraded quality, but also that there are no users downstream to use unused portions of water that have passed through the project. It is at this point that IID's critics erroneously claim that the water not specifically used to meet evapotranspirative demands of IID's crops is being wasted. Indeed, upstream diverters have diverted water from the Colorado River and a portion of it returns to the River. The fields and crops of these irrigation districts have in fact benefited from more than the amount of water transpired by the crops. In other words, the amount of water passing through upstream projects as return flow has served a number of beneficial purposes beyond that of strictly meeting evapotranspiration (ET) demand. These beneficial uses include adequate irrigation uniformity necessary to meet ET and leaching demands. These are the same types of beneficial uses that IID gains by having a portion of water flow through the project. Obviously, consideration of return flow is important in addressing macro interpretations of irrigation efficiency, but to separate the terminal user from the system is invalid. If praise or condemnation of a particular irrigation district are the order of the day, then the comparison of individual irrigation projects should therefore be made on a similar basis.

The fact that drain water exiting IID to the Salton Sea does not constitute return flow available to others along the Colorado River is simply not a matter of irrigation practice within IID, it is a matter of geography and the act of creating a transbasin diversion which took place over one hundred years ago. Furthermore, the lack of a well positioned downstream user (additional multiplier effects) cannot therefore be viewed as an indictment of the terminal irrigation project's operation.

San Joaquin Valley and CDWR Efficiency Assessments

San Joaquin Irrigation Background

The San Joaquin Valley, within the center of California, has approximately 5 million acres of irrigated land on the valley floor. Many of the irrigated lands within the Valley represent terminal users of water, with surface and sub-surface drainage flowing into saline sinks. Irrigation water is often derived in part from saline groundwater sources. Many fields are of soils which are poorly drained and salt and selenium effected. Reuse and disposal of contaminated irrigation drainwater is a major environmental problem as is the maintenance of adequate soil leaching.

The climate of the San Joaquin Valley can be described as follows:

Annual Precipitation	10.89 inches/year
Maximum Temperature	98 degrees F
Minimum Temperature	37 degrees F
Mean Temperature	63 degrees F
Growing Season	270 days (approximately)

Soil properties vary drastically from east to west across the San Joaquin Valley, between the Coastal and Sierra Nevada Mountain Ranges. Soils on the east side of the valley are coarse textured, deep, and well-drained. Depth to the water table is often only 10 m, and extends several hundred meters down. On the west side, however, soils were formed from the geological weathering from marine sediments, creating fine-textured soils containing salts and trace amounts of numerous other elements. The most prevalent soil texture is clay loam, often containing layers of very low permeability.

On the western part of the valley, soil permeability can be as low as 0.01 in/hr, and rarely exceeds 0.2 in/hr. The depth to the bedrock is often 20 to 40 inches. This soil is not conducive to agricultural use; in these areas runoff and erosion are common. The problem is complicated further due to the fact that the runoff contains salt and other trace elements from the soil that are transported toward the middle of the valley and eventually the San Joaquin River or various sinks. Deep percolating water associated with groundwater basins on the west side is essentially lost for further use due to high salinity,

The ten major crops in the San Joaquin Valley are:

1. Pasture
2. Cotton
3. Alfalfa (hay)
4. Vineyard (table grapes)
5. Almonds
6. Deciduous orchard
7. Tomatoes
8. Small grains
9. Citrus*
10. Potatoes

*Field plot data collected by F. Aljibury, University of California Cooperative Extension.

These ten crops combined account for 85% of the total crops in the valley. Current methods for irrigation include flood irrigation and drip irrigation. Previous methods include the contour or the border-check method.

The San Joaquin Valley's sources of water include surface water and groundwater wells. Water is received from the California Aqueduct and state water projects, as well as the San Joaquin River system.

The conveyance of water within the San Joaquin Valley is accomplished by a complex and often interconnected canal system. Distribution of irrigation water is accomplished by means of a combination of canal and pipeline systems. The distribution system is nearly all concrete lined. There are smaller earthen channels off the main canals which supply water to individual towns and farms. Irrigated lands on the east side of the valley are better suited for co-management with groundwater recharge and reuse than those on the west side due to geology and better water quality in general. West side farms benefit from this in that irrigation water not used by crops percolates to the groundwater basins, where it is usually pumped up and reused. On both west and east side farms, first cut water from canals is used for salt-sensitive crops such as vegetables and fruit. Groundwater is often blended with higher quality surface diversions from canals for purposes of irrigating more salt tolerant crops. Most water not consumed or lost to saline groundwater eventually drains into the San Joaquin River and flows northwest into the San Francisco Bay.

California Department of Water Resources Irrigation Efficiency Investigations and Methods

In April of 1992, the California Department of Water Resources (CDWR) reported the findings of its Bay-Delta Agricultural Sub-Workgroup #1 to the State Water Resources Control Board regarding the San Joaquin Valley (Roos, 1992). The CDWR has had input from a range of experts on irrigation water use, including Dr. Blaine Hanson and Dr. Charles Burt. The efficiency term used by the working group and by the State of California is called Seasonal Application Efficiency, which has been used as a standard for comparing and improving irrigation efficiencies within the state. Seasonal Application Efficiency (SAE) is defined as:

$$SAE = \frac{EAW + LR + CP}{AW}$$

where:

- EAW = Evapotranspiration of applied water
- LR = Leaching requirement
- CP = Water for cultural practices
- AW = Water applied on-farm, normally the farm headgate amount. (Tailwater recycled internally is not counted but if tailwater is used on a different field, it is part of the field's applied water).

In the report of findings, the workgroup identified goals associated with water conservation within the San Joaquin Valley. These are:

1. Maintain present level of crop production.
2. Maintain present amount of annual net recharge to groundwater in non-saline sink areas.
3. Reduce annual net recharge to groundwater in saline sink areas (if possible) by increasing irrigation efficiencies to the maximum reasonable target efficiency for irrigation.
4. Maintain salt balance in the crop root zone as necessary to maintain present crop productivity.

The findings stated that "The Sub-Workgroup agreed that an appropriate average target on-farm irrigation efficiency for the San Joaquin Valley should be 73%. The 73 percent is calculated as a Seasonal Application Efficiency (SAE) which is defined as follows:" (see above definition). This on-farm efficiency was based on an assumed distribution uniformity (DU) of 80% and further that "Information provided by experts indicated that 80 percent DU may represent a maximum and that a more realistic average was 70-80 percent."

In the report it is stated that estimates of key parameters were based on limited actual data and that expert judgment was necessary to make estimates of uniformity and efficiency. Specific data were collected from farms within Detailed Assessment Units (DAU). It is further stated that: "Reasonable seasonal application efficiency (SAE) reflects distribution uniformity (DU) and leaching requirements (LR). The SAEs should incorporate allowances for cultural practices (CP), such as frost protection, extreme heat protection, weed control, and rice paddy water. In most areas the unit CP amounts are small, probably less than 0.2 of a foot. A 73 percent SAE would provide protection of beneficial use with 80 percent DU and a 5 percent LR, assuming continuation of present water quality." It was pointed out in footnote, that "Five percent [leaching fraction] is an average which assumes supply water quality of 0.4 EC or 250 ppm TDS; amounts can vary depending on salt tolerance of the specific crop and quality of water supply."

Drs. Burt and Hanson were identified in the report as providing input specifically pointing out limitations to the feasibility of managing water conservation. "The feasibility of managing applied water to minimize deep percolation is limited by weather related variations in ET, by soil variability within fields, and by other uncertainties. The Sub-Work Group has the benefit of the advice of two irrigation experts, Dr. Charles Burt from Cal Poly, San Luis Obispo, and Dr. Blaine Hanson, UC Davis. Both of these men felt that 80 percent DU may be at the high end of that attainable under field conditions. A more realistic range may be 70 to 80 percent, at least for existing irrigation systems. Apparent SAE values higher than 73 percent often mean some under-irrigation or crop stress in part of the irrigated field or crop use of shallow ground water. Inadequate leaching may also be a factor."

A summary of determinations of SAE were presented in the findings which reflect the limited data available. In the case of these estimates it needs to be pointed out that under irrigation of the fields was assumed and therefore the evapotranspiration of applied water (ETAW) was modified to reflect this. ETAW refers to the seasonal ET minus effective precipitation. Under-irrigation would of course tend to increase efficiencies but produce less than optimal yields. Additionally, the estimates are based on a LR of 5% which may be too low for salt effected fields. Inclusion of a higher LR and also of water required for cultural practices would tend to raise efficiencies. The findings report states: "Currently estimated efficiencies, neglecting CP water, are shown in Table 1 by planning sub-area. A 5 percent leaching fraction has been assumed. Long range considerations must deal with salt balance. In areas where deep percolation water is reused, efficiencies which are too high may degrade ground water where reuse for most purposes is precluded because of high TDS concentrations in the percolate."

Table 1 Estimated SAE for San Joaquin Planning Sub-Areas, (from CDWR Workgroup #1s Report of Findings)

Sub-Area	Cropped Acreage (acres x 1000)	Modified ETAW (AF x 1000)	Leaching Requirement (AF x 1000)	Crop Irrig. Requirement (AF x 1000)	Applied Water (AF x 1000)	Average Field SAE (percent)
Kern Valley	897	2,011	101	2,112	2,760	77
Kings Kaweah Tule	1,693	3,748	187	3,935	5,224	75
San Luis WestSide	612	1,260	63	1,323	1,674	79
Valley Eastside	1,031	2,301	115	2,416	3,332	72
Valley Westside	437	960	48	1,008	1,436	70
Total	**4,670**	**10,280**	**514**	**10,794**	**14,426**	**75**

It should be pointed out that the ETAW was modified by the researchers to account for under irrigation. The report describes under irrigation conditions related to areas studied in attachment 3 of the report under the heading 'Under-irrigation Rationale'. The attachment states: "There are two primary reasons for under irrigation in the San Joaquin Valley. The first is soils which have infiltration problems in which not enough water can be moved into the rooting zone during the irrigation season. These are mostly heavy soils and soils which tend to seal up when water is applied. An estimated 15 percent of the Valley lands fall into this category. Estimated Actual ET is 95 percent of full crop ET. This works out to around a 1 percent shortfall in overall ET. The second reason for under irrigation is lack of adequate water supplies. Mostly this is occurring on the San Luis West Side, areas on the fringe of the east side of Kings-Kaweah-Tule Friant Kern Canal service areas which are short on ground water supply, and perhaps some areas of western Kern County."

<u>CDWR Mobile Laboratory Irrigation System Evaluations</u>

The mobile laboratory program is part of CDWR's efforts to better understand actual irrigation operations within California and regional irrigation efficiency. This program has been conducted by a number of the same experts as were involved with the previously described study of the San Joaquin Valley. In 1993, a draft report by Hanson et al. was produced that reflects an analysis of the results of the mobile laboratory program, a brief summary of this report is presented here with regard to this review of irrigation efficiency because it reflects the efforts and findings of California agricultural water management experts. Furthermore, much of the knowledge gained has been used by CDWR to formulate planning strategies concerning California's water plan, as reflected by the CDWR Bulletin 160 series on California Water Plan Updates.

The mobile laboratory program is a good example of actual irrigation efficiency studies that need to take place in a comprehensive and detailed manner in order to get a clear picture of the state of irrigation practice and baseline irrigation efficiencies within specific regions of the state. Dr. Keller summarized the need for information exchange regarding water conservation programs in his presentation of *Reengineering Irrigation to Meet Growing Freshwater Demands*, as presented at the 2000 ASAE National Irrigation Symposium. In his presentation describing the CALFED Agricultural Water Use Efficiency Program (Ag WUE), Dr. Keller stressed five points regarding joint fact finding.

"Joint fact-finding rests on a few key ideas (McCreary et al., 1992). The first is that rather than withholding information for strategic advantage, the interested parties pool relevant information. A second feature of joint fact-finding involves face-to-face dialogue between technical experts, key stakeholders and decision makers. Third, this process places considerable emphasis on "translating" technical information – text, graphics, videos, and oral presentations – into a form that is accessible to participants in the dialogue. The fourth significant aspect of the process is scientific stakeholder agreement and to narrow areas of disagreement and uncertainty. A fifth idea is to develop a "single negotiating text" to record the results of the fact-finding process. This simply means that participants in the negotiation develop a single document based on the inputs of the stakeholders and technical experts to focus discussion, rather than generating competing a version of facts and recommendations."

It is in this way that CDWR experts have acted to accomplish the development of baseline irrigation efficiency assessments, including the activities of the mobile laboratory. The mobile laboratory evaluation report focuses mostly on irrigation uniformity, as regionally specific estimates of irrigation efficiency were not reported.

Undoubtedly, the mobile laboratory has collected data which can be used for this purpose. The evaluation report states that: "During the past 10 years, mobile laboratories sponsored by state and federal agencies have evaluated irrigation systems for growers. Data collected by these laboratories can help assess the uniformity and efficiency of the applied water and identify problems with system design or management. Recommendations then are made for improving system or management changes. Thus far, [since 1993] 936 agricultural irrigation systems have been evaluated. These evaluations provide a data base on performance characteristics of various irrigation systems and on problems in both design and management of an irrigation method. Thus, the objectives of that study were: 1) develop a data base of the information contained in the mobile laboratory reports, 2) analyze the data for uniformity and efficiency characteristics of the various irrigation methods, and 3) identify common characteristics and problems related to system performance. The reports of the mobile laboratories were provided by the Office of Water Conservation and the State Department of Water Resources." Additional mobile laboratory field evaluations, since the time of this report have been very limited due to limited funding (Baryohay, 2003 personal communication).

1997 Draft Report, Agricultural Water Conservation Unit, CDWR

A draft report was prepared by the CDWR for Bulletin 160-98, California Water Plan Update. This report is believed to include relatively up to date information regarding CDWR's understanding of and position on the costs of improving irrigation water use efficiency. Within this report, CDWR states that the statewide on-farm irrigation efficiency is 73 percent. Additional summaries of three regions are presented along with cost estimations associated with the improvements in irrigation efficiency based on tiers of efficiency for the years 1995 and 2020.

The lower Colorado River Region is summarized as follows:

"The data on beneficial water use for different crops is generally available, while data for water at the farm level, including DU, is only available from Coachella Valley Mobile Lab, which has conducted over 600 irrigation system evaluations within the Coachella Valley Water District irrigated area. In order to estimate irrigation efficiency for the entire region, information reported by other major agricultural water suppliers is used. Therefore, an equitable approach is to calculate a weighted average taking into account the acreage irrigated by the other two main agricultural water suppliers in the region, Imperial irrigation District and Palo Verde Irrigation District. The weighted average for a seasonal on-farm irrigation efficiency, representative of the Colorado River Region, is 76%."

The two other regions addressed in this draft report are Tulare Lake Region and the South Coast Region, with average seasonal on-farm irrigation efficiencies of 75% and 76% respectively. The California Water Update, Bulletin 160-98 states that "It is assumed that by 2020 SAE will reach 73 percent in all regions of California, averaged across crop types, farmland characteristics, and management practices. The DU of irrigation methods limits SAE. The average DU of irrigation systems in California is currently in the 70 to 75 percent range, based on irrigation system evaluations conducted by the Department, resource conservation districts, water districts and others. By 2020, the average DU is expected to be about 80 percent. An irrigation method with a DU of 80 percent can achieve a maximum SAE of about 73 percent, assuming that irrigation events are properly timed, the soil is well drained, and none of the field is under irrigated."

Conclusions

The Most notable conclusion from the above review of irrigation efficiency is the trend in definitions of irrigation efficiency to become more developed. Specifically, that irrigation efficiency as a concept has, over the years changed somewhat to address beneficial use more directly. The change in irrigation efficiency terms reflects the increased value of water and the various phases of water development within a basin. Terms and concerns more directly addressed in the later definitions are aimed at identifying, more intricately the realities of irrigation practice and include leaching requirements. Furthermore, irrigation efficiency has been tied to irrigation uniformity, which is a function of irrigation methods and practices, which are a direct result of environmental conditions including soils and evapotranspiration and the presence of salts in the irrigation water. The concepts of irrigation efficiency have become an integral part of regional and state water management programs directed largely at water conservation and water quality concerns.

California water management programs related to the CALFED program, as well as other programs of the CDWR, have developed definitions for the key terms relating to the definition of irrigation efficiency. California has estimated irrigation efficiencies for the various regions of the State. The California Water Update, Bulletin 160-98 states that "It is assumed that by 2020 SAE will reach 73 percent in all regions of California, averaged across crop types, farmland characteristics, and management practices. The DU of irrigation methods limits SAE. The average DU of irrigation systems in California is currently in the 70 to 75 percent range, based on irrigation system evaluations conducted by CDWR, resource conservation districts, water districts and others. By 2020, the average DU is expected to be about 80 percent. An irrigation method with a DU of 80 percent can achieve a maximum SAE of about 73 percent, assuming that irrigation events are properly timed, the soil is well drained, and none of the fields are under irrigated."

Wapato Irrigation Project – Yakama Indian Reservation

Additional information is presented regarding the comparison between the Wapato Irrigation District (WIP) and the Yakama Indian Reservation. The Soil Conservation Service (SCS) Soil Survey of the Yakama Indian Reservation characterizes the climate of the area as follows:

Annual Precipitation	7.11 inches/year
Maximum Temperature	101 degrees F
Minimum Temperature	3 degrees F
Mean Temperature	52 degrees F
Growing Season	181 days

The WIP is located in the lower Yakima River Basin of Washington and lies to the east of the Cascade Mountain Range. The area addressed by the SCS contains 120,000 acres of irrigable land and is broken up into three different units, The Wapato Unit, the Bench Unit, and the Satus Unit.

Within the Wapato Unit, the most prevalent soil classification is the Ashues-Naches Association. The soils are characterized as deep, well drained, medium-textured soils formed in old alluvium and underlain by gravelly material. The soils along Toppenish Creek and soils around the city of Toppenish are characterized as deep, somewhat poorly drained, medium textured and moderately fine textured soils formed in alluvium and are of the Toppenish-Umapine Association. Soils along the Yakima River are characterized as deep, somewhat excessively drained and well drained, medium textured and moderately coarse textured soils formed in recent or old alluvium and underlain by very gravelly material, and are in the Weirman Association.

Within the Bench Unit, the majority of the soil is classified as Warden-Shano soils as they are deep, well drained, medium textured and moderately coarse textured soils formed in wind lain deposits underlain by lake sediments, or in deep wind lain deposits. A portion of the Bench Unit that lies along Toppenish Creek contains soils in the Toppenish-Umapine Association, as described above. A small portion of the unit just east of the town of White Swan contains soils that are deep, well-drained, medium textured and moderately coarse textured soils formed in windblown deposits underlain by lake sediments and classified within the White Swan Association.

The Satus Unit is comprised of four major types of soils. Soils along the Yakima River are primarily of the Weirman Association. The soils along Satus Creek are of the Toppenish-Umapine Association. The soils of the upper Satus area are deep, well drained, medium textured and moderately coarse textured soils of the Warden-Shano Association. The lower and middle portion of the Satus Unit are deep, somewhat excessively drained, coarse textured soils formed in windblown sand that in places is underlain by sediments classified as the Quincy-Henzel Association.

The ten predominant crops grown within the boundary of the WIP are displayed in Table 2 below. There are approximately 40 crops grown within the WIP. Approximately 73,400 acres are currently used for crops in the WIP, with room for approximately 40,000 acres for expansion. All data were obtained from BIA annual crop reports from 1993-1997.

Table 2 Top Ten Crops – Wapato Irrigation Project, Yakama County, WA.

Crop	Crop Type	Salt Tolerance	Average Acreage	%of Total Acres	Running Sum	Count
Hops	Field	N/A	10297	14.0%	14.0%	1
Apples	Orchard	S	9347	12.7%	26.8%	2
Alfalfa	Field	MS	9317	12.7%	39.5%	3
Wheat	Field	T	7703	10.5%	49.9%	4
Corn	Field	MS	6905	9.4%	59.4%	5
Peppermint	Garden	N/A	5906	8.0%	67.4%	6
Sweet Corn	Field	MS	4650	6.3%	73.7%	7
Spearmint	Garden	N/A	3008	4.1%	77.8%	8
Grapes	Orchard	MS	2946	4.0%	81.8%	9
Asparagus	Garden	T	2244	3.1%	84.9%	10

N/A indicates that salt tolerance was not found in tables from Francois and Maas (1978, 1985).

The WIP's main source of water is the Yakima River, which supplies approximately 93% of the irrigation water for the area. Surface water allocated to the WIP is approximately 655,000 acre-feet per year during the irrigation season, with additional rights for winter and flood water. There are also two smaller creeks that serve as water sources for the project. Simcoe Creek and Toppenish Creek flow into the area from the west, and are used to irrigate some of the land in the southern areas of the project. Satus Creek flows into the Satus Unit, but no water is diverted from the creek for irrigation purposes. There are many groundwater wells in place, but most of this water is alluvial and derived from Yakima River diversions.

Water is diverted from the Yakima River at the northern edge of the WIP, near Union Gap. Water is then pumped into the Main Canal, which serves the area. Two additional canals are served from the Main canal. The Unit 2 Pump Canal receives water remaining from canals subordinate to the Main Canal, other canals, and water from Toppenish creek.

Except for low head pumping facilities, the conveyance and distribution of water within the WIP is chiefly a gravity system. Within the Bench and Wapato Units, the lateral and sub-lateral conveyances are typically earthen channels. Because the soils are underlain by alluvial deposits, water tables are close to the surface. An elaborate system of surface and subsurface drains has been constructed to maintain root zone drainage and to recapture drainage water. It is this water that is transported, via the drain systems within the Bench and Wapato units, and used for irrigation in the Satus Unit. Where return flow is used for irrigation, buried irrigation pipes are used to transport and deliver water. It is estimated that approximately 240,000 acre-feet of return flows are used for irrigation annually.

Two methods were used to calculate the overall efficiency of the WIP, one recognizing return flow and one without. Table 3 summarizes the efficiency estimates for the WIP. The calculations are explained as follows:

$$\mathit{efficiency} = \frac{\text{water consumed by crops}}{\text{Inflow to system - Outflow from system}} * 100$$

and:

$$\mathit{efficiency} = \frac{\text{water consumed by crops}}{\text{Inflow to system}} * 100$$

Including return flow in the calculation results in an overall efficiency of 77.7%. Not including return flow results in 37.4% overall efficiency.

Additional estimates of overall efficiency were determined for the combination of the Bench Unit and Wapato units and for the Satus Unit, located just southeast of the Bench/Wapato unit. The Satus Unit is served almost completely from Bench and Wapato unit drainage. Water duties were estimated for all three units based on the acreage weighted water duty. This was necessary in order to have an component efficiencies that balance with the total overall efficiency.

Because return flow is not gaged within the greater project, it is not possible to address return flow for the intermediate unit separately. Using the second method, the efficiency was calculated as 29.2%. For the Satus parcel, the water diverted for irrigation usage was computed by summing three different gage flows. Although a gage measurement is not known for the boundary of the parcel, three separate gage measurements could be used to determine the total amount diverted. Those three gages are the East and West Lateral (just off the Satus Creek) and a pump downstream which pumps water into the Satus #2 Canal. Summing three figures shows a total diversion of 152,510 acre-ft/year determined and is used to calculate an efficiency of 44.6%.

Table 3 Overall Efficiency Estimates for WIP

Unit	**Overall Efficiency** (with return flow)	**Overall Efficiency** (without return flow)
Total	77.7%	37.4%
Bench/Wapato Unit	N/A	29.2%
Satus Unit	44.6%	N/A

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EFFICIENCY IN IRRIGATION

by

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October 1990

Attachment 2

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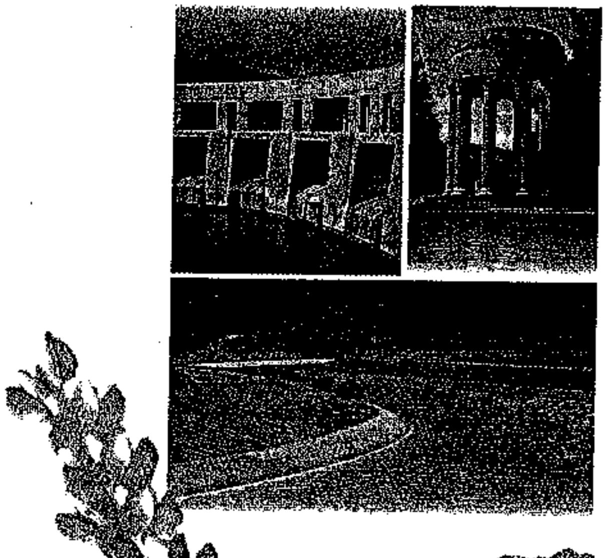

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Pete Wilson
Governor

Douglas P. Wheeler
Secretary for Resources
The Resources Agency

David N. Kennedy
Director
Department of Water Resources

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DRAFT
May, 1997

Cost of Improving Irrigation Efficiency, A Demand Management Option

Prepared for

Bulletin 160-98
California Water Plan Update

By

Agricultural Water Conservation Unit,
California Department of Water Resources

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IRRIGATION EFFICIENCIES[1]

by

Vaughn E. Hansen[2]

Proper handling of irrigation water requires methods of measurement and evaluation of performance. Necessity has resulted in the development and acceptance of certain basic concepts which are very useful. However, as water becomes more scarce, as the need becomes more pressing for maximum economic returns, new and more complete methods of evaluation become necessary. This paper deals primarily with new concepts of irrigation efficiency which are necessary to evaluate properly the irrigation practice.

Water Conveyance Efficiency

Two fundamental concepts of irrigation efficiency which have been accepted widely are water conveyance efficiency and water application efficiency defined in table 1.

When both concepts were developed, most of the irrigation water came from diversions from streams or reservoirs. The losses which occurred in conveying the water from a diversion to the farm were often excessive. The concept of water conveyance efficiency was developed to evaluate this loss.

Water Application Efficiency

Having conveyed the available water to the farm through costly diversions and conveyance structures, the need was apparent to apply the water efficiently. Research (1) showed that often times considerably more water

1/ This paper is a result of research conducted at Logan, Utah, under the Research and Marketing Act, Project W-29, cooperatively with the Utah Agricultural Experiment Station, the eleven Western States, Hawaii, Alaska, and the Agricultural Research Service, U.S.D.A.

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AN ANALYSIS OF MOBILE LABORATORY IRRIGATION SYSTEM EVALUATION DATA: AGRICULTURAL SYSTEMS

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Introduction

During the past 10 years, mobile laboratories sponsored by state and federal agencies have evaluated irrigation systems for growers. Data collected by these laboratories can help assess the uniformity and efficiency of the applied water and identify problems with system design or management. Recommendations then are made for improving system performance. These evaluations provide site-specific information to aid in making system or management changes.

Thus far, 936 agricultural irrigation systems have been evaluated. These evaluations provide a data base on performance characteristics of various irrigation systems and on problems in both design and management of an irrigation method. Thus, the objectives of this study are: 1) develop a data base of the information contained in the mobile laboratory reports, 2) analyze the data for uniformity and efficiency characteristics of the various irrigation methods, and 3) identify common characteristics and problems related to system performance. The reports of the mobile laboratories were provided by the Office of Water Conservation of the State Department of Water Resources.

Evaluating Irrigation System Performance

Major performance characteristics of irrigation systems are uniformity of applied or infiltrated water and irrigation efficiency. The uniformity is described by the distribution uniformity, which is the minimum depth infiltrated divided by the average depth infiltrated. The minimum depth infiltrated frequently is defined as the average of the lowest one-fourth of the measured or estimated amounts of infiltrated water, called the average of the low quarter. Irrigation efficiency is the amount of water beneficially used divided by the average amount of applied water. If the amount of beneficial use equals the amount infiltrated in the low quarter, then the distribution

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IRRIGATION PRINCIPLES AND PRACTICES

Third Edition

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New York · London · Sydney

CHAPTER 1 IRRIGATION—WORLDWIDE

Irrigation is an age-old art. Historically, civilization has followed the development of irrigation. Civilizations have risen on irrigated lands; they have also decayed and disintegrated in irrigated regions. Most men who are well informed on irrigation are certain of its perpetuity, as long as it is intelligently practiced. Others think that a civilization based on agriculture under irrigation is destined sooner or later to decline, because some ancient civilizations based on irrigation have declined. The duration of civilized peoples is probably dependent on many factors, of which a permanently profitable agriculture is vitally important. Some of the principles and practices essential to permanent and profitable agriculture under irrigation are considered in this volume.

1.1 CENTURIES OF IRRIGATION

The antiquity of irrigation is well documented throughout the written history of mankind. Genesis mentions Amraphel, King of Shinar, a contemporary of Abraham, who is probably identical with Hammurabi, sixth king of the first dynasty of Babylon. He developed laws, bearing the name of Hammurabi, indicating that the people had to depend upon irrigation for existence. One of the laws of Hammurabi states that if a man neglects to strengthen his bank of the canal and waters carry away the meadow, the man in whose bank the breach is opened shall render back the corn which he has caused to be lost.

The letters of Hammurabi about 2000 B.C. reveal a busy, governmental administrator who wastes no words when instructing his officials:

> To Sid-Indiannam, Hammurabi speaks as follows: Gather the men that have fields along the Damanum Canal to clear out the Damanum Canal. Within this month, let them complete the digging of the Damanum Canal.

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Effective Efficiency: A Water Use Efficiency Concept For Allocating Freshwater Resources

by Andrew A. Keller, Vice President, and Jack Keller, Chief Executive Officer, Keller-Bliesner Engineering, Logan, Utah.

Efficiency is "the ratio of the effective or useful output to the total input in any system."

(American Heritage Dictionary)

This paper was originally published as Discussion Paper No. 22 by the Center for Economic Policy Studies, Winrock International, 1995.

The classical concepts of irrigation efficiency have been appropriate for farmers making irrigation management decisions and for planners designing irrigation conveyance and application systems. But applying classical efficiency concepts to water basins as a whole leads to incorrect decisions and, therefore, to faulty public policy. The critical difference is that in managing irrigated fields or designing an irrigation system, the total input is the amount of water that farmers must order or designers must handle, but this is not true for a water basin as a whole. As water flows through a basin, it may be used many times. Consequently the total input for each use-cycle is only the water that is effectively consumed.

Classical efficiency concepts systematically ignore the return flows from any given application of irrigation water. If, for example, the (classical) irrigation efficiency is 50% (ignoring leaching requirements), that means 50% of the water delivered is lost to the atmosphere through crop evapotranspiration. But what happens to the other 50%? The answer is, of course, that most of it flows to surface and subsurface areas. This return flow is usually captured by downstream pumps and diversions and reused. That is, one user's inefficiency can be the next users' supply of water. When the water is reused, the overall basin-wide efficiency increases. Thus, the irrigation system as a whole can be much more efficient than any of its parts.

A new concept, which we call *effective efficiency*, captures the effects of both recycling and changes in water quality[1] that occur during each use-cycle or a sequence of use-cycles. In this discussion, we focus on irrigation efficiencies and the degradation of freshwater resources resulting from salt concentration and salt pick-up or loading. We call the effective water use efficiency of an irrigation system, or the effective irrigation efficiency, E_e.[2]

Classical Irrigation Efficiency

The irrigation literature contains many classical efficiency terms. The basic concept of irrigation efficiency, I_e, was set forth by Israelsen (1950) as the ratio of the irrigation water consumed (evaporated) by crops, U_{ci}, to the irrigation water delivered from a surface or groundwater source to the canals or farm headgates, V_D:

$$I_e = \frac{\textit{Irrigation Water Evaporated by Crops}}{\textit{Water Diverted, Delivered, or Applied}} = \frac{U_{ci}}{V_D} = \frac{CropET\ P_e}{V_D} \qquad (1)$$

where *CropET* is the crop transpiration and evaporation or evapotranspiration, *ET*, and P_e is the effective precipitation. This early definition, which has been accepted by irrigationists worldwide, is an appropriate but limited parameter for irrigation design. It applies only to the quantity of water that must be handled (pumped, conveyed, etc.) to accommodate an estimated amount of beneficial use. For design purposes, it is limited because it omits the necessary leaching water.

As irrigation water is transpired by crops and evaporates from the soil surface, salts remain behind and accumulate in the soil. To maintain a favorable salt balance for optimum crop production, these residual salts must be periodically leached from the soil by applying excess water. The ratio of the minimum amount, V_{LR}, of the applied irrigation water (in excess of $CropET - P_e$, or U_{ci}) that must pass below the crop root zone to maintain a favorable salt balance is called the leaching fraction or requirement, *LR*:

$$LR = \frac{V_{LR}}{U_{ci} + V_{LR}} \qquad (2)$$

The leaching requirement is specific for each combination of irrigation water quality and crop because crops differ in their tolerance to soil salinity. It is also a function of the type of irrigation application system, the frequency of irrigations, and to a limited extent, soil texture. Fortunately, the leaching requirement for different crops and irrigation water qualities has been well researched and documented (Ayers and Wescot 1985), so we will only consider the leaching requirement for typical surface and sprinkler irrigation application methods.[3]

Consequently we expand the classical concept of irrigation efficiency in equation (1) to account for leaching requirements (and we designate expanded classical efficiency as E_i):

$$E_i = \frac{I_e}{1 - LR} \qquad (3)$$

or

$$E_i = \frac{(CropET - P_e) + V_{LR}}{V_D} = \frac{U_{ci} + V_{LR}}{V_D} = \frac{U_{ci}}{(1 - LR)V_D} \qquad (4)$$

Attachment 8

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NATIONAL IRRIGATION SYMPOSIUM

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Todd P. Trooien

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Look for ways to reduce all inputs for a crop (including management) while increasing profitability.

Develop management tools and algorithms for irrigation, which are easy to understand and use.

Understand the foliar feeding of plants and recognize that under certain sprinkler regimes the entire application may be applied to only the leaves and stems of a plant.
Look for economic soil amendments to change the characteristics and water holding capacity on sandy soils.

Look for methods to economically reclaim waterlogged fields.

Research ways to more economically drain fields.

Determine ways to use controlled leaching and ways to hold salts in the field, but below the root zone.

Develop a fact-based response to the anti-irrigation lobby, which shows the positive side of irrigation and its beneficial results on our society and the world. Help develop the positive will of our people.

Consider the biological pesticide industry and how to use this tool in irrigation. Remember we have the capacity to make frequent light application of both chemicals and biological treatments to the crop.

ving said all of this, I believe that if we have the political will to prepare for the expected rease in population, fund our research, and share the knowledge, we can solve the future issues food, clothing and shelter for mankind. I would like to be here to see things 50 years from now, t by then I will be 117 years old. I doubt that I will make it ... and beside they will need my ace for one of my great, great grand children. Thank you for listening.

REENGINEERING IRRIGATION TO MEET GROWING FRESHWATER DEMANDS

Jack Keller*

ABSTRACT

This paper provides a conceptual framework for river basin analysis and planning. A general development progression is described that all river basins will follow in some manner as their water supplies are developed to meet growing demands. Water development progress from the exploitation to the conservation and finally to the augmentation phases (or eras). The specific progression that any single basin will follow is determined by the relative costs and availability of the development options in that basin, the amount of water reserved to meet ecological needs, and other factors. The concept of river basin closure, which occurs when water use approaches the available supply, is presented and its implications to water resource planning examined. It is during the conservation era that significant increases in the beneficial consumptive use portion of the developed water supply are made. The remaining focus of this paper is water management planning during the conservation era, which includes a discussion of the need and a strategy for reengineering irrigation systems and implementing conservation programs.

KEY WORDS. Irrigation, Development, Reengineering, Modernization, Conservation, Water Resources, CALFED.

PRELUDE

I appreciate the opportunity to share my thoughts on the need to modernize our irrigation systems at this Keynote session of the Fourth National Irrigation Symposium. The written text is a synthesis of my thought regarding the need for our irrigation community to commit to providing their talents and ingenuity to in effect "reengineer irrigation[1]" to meet the growing demands on the freshwater resources in the Western United States. Much of it is taken from five papers (Burns et al., 2000, CALFED Planning Team, and Keller et al., 1993, 1996, 1998, and 1999) of which I was the principal or co-author. Sections of the text are new but some are taken from these papers and only slightly modified to weave together the following story. The story begins with the phases of water basin development from open for essentially unfettered and inexpensive exploitation to being closed to further development except by freeing up water through conservation or augmenting supplies with new water. I and a few of my colleagues call this the progression from the era of water resources exploitation to the conservation era (in which we find ourselves today) and then on to the augmentation era.

The section on the development phases concludes with the costs of developing water supplies and the societal implications of closure and is followed by discussions of: strategies for modernizing irrigation systems; and implementing conservation programs. The last section contains excerpts form the recently released framework for the CALFED Bay-Delta Restoration Program and its Agricultural Water Use Efficiency component for which I serve as the Senior Technical Adviser/Integrator. The CALFED Program represents what promises to become the world's largest reengineering effort of irrigation systems for environmental restoration and water quality purposes.

In conclusion I want to recognize the following co-authors for their contributions to the papers I have used so liberally; my son Andy Keller whom I have the joy of working collaboratively with; Joe Burns, Grant Davids, Kirk Dimmitt, the team I worked with on verifying water savings for the

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[1] I use reengineering irrigation more or less interchangeably with modernization of irrigation systems.

Attachment 9

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[1] I use reengineering irrigation more or less interchangeably with modernization of irrigation systems.

Look for ways to reduce all inputs for a crop (including management) while increasing profitability.

Develop management tools and algorithms for irrigation, which are easy to understand and use.

Understand the foliar feeding of plants and recognize that under certain sprinkler regimes the entire application may be applied to only the leaves and stems of a plant.
Look for economic soil amendments to change the characteristics and water holding capacity on sandy soils.

Look for methods to economically reclaim waterlogged fields.

Research ways to more economically drain fields.

Determine ways to use controlled leaching and ways to hold salts in the field, but below the root zone,

Develop a fact-based response to the anti-irrigation lobby, which shows the positive side of irrigation and its beneficial results on our society and the world. Help develop the positive will of our people.

Consider the biological pesticide industry and how to use this tool in irrigation. Remember we have the capacity to make frequent light application of both chemicals and biological treatments to the crop.

ving said all of this, I believe that if we have the political will to prepare for the expected rease in population, fund our research, and share the knowledge, we can solve the future issues food, clothing and shelter for mankind. I would like to be here to see things 50 years from now, by then I will be 117 years old. I doubt that I will make it ... and beside they will need my ace for one of my great, great grand children. Thank you for listening.

REENGINEERING IRRIGATION TO MEET GROWING FRESHWATER DEMANDS

Jack Keller*

ABSTRACT

This paper provides a conceptual framework for river basin analysis and planning. A general development progression is described that all river basins will follow in some manner as their water supplies are developed to meet growing demands. Water development progress from the exploitation to the conservation and finally to the augmentation phases (or eras). The specific progression that any single basin will follow is determined by the relative costs and availability of the development options in that basin, the amount of water reserved to meet ecological needs, and other factors. The concept of river basin closure, which occurs when water use approaches the available supply, is presented and its implications to water resource planning examined. It is during the conservation era that significant increases in the beneficial consumptive use portion of the developed water supply are made. The remaining focus of this paper is water management planning during the conservation era, which includes a discussion of the need and a strategy for reengineering irrigation systems and implementing conservation programs.

KEY WORDS. Irrigation, Development, Reengineering, Modernization, Conservation, Water Resources, CALFED.

PRELUDE

I appreciate the opportunity to share my thoughts on the need to modernize our irrigation systems at this Keynote session of the Fourth National Irrigation Symposium. The written text is a synthesis of my thought regarding the need for our irrigation community to commit to providing their talents and ingenuity to in effect "reengineer irrigation[1]" to meet the growing demands on the freshwater resources in the Western United States. Much of it is taken from five papers (Burns et al., 2000, CALFED Planning Team, and Keller et al., 1993, 1996, 1998, and 1999) of which I was the principal or co-author. Sections of the text are new but some are taken from these papers and only slightly modified to weave together the following story. The story begins with the phases of water basin development from open for essentially unfettered and inexpensive exploitation to being closed to further development except by freeing up water through conservation or augmenting supplies with new water. I and a few of my colleagues call this the progression from the era of water resources exploitation to the conservation era (in which we find ourselves today) and then on to the augmentation era.

The section on the development phases concludes with the costs of developing water supplies and the societal implications of closure and is followed by discussions of: strategies for modernizing irrigation systems; and implementing conservation programs. The last section contains excerpts form the recently released framework for the CALFED Bay-Delta Restoration Program and its Agricultural Water Use Efficiency component for which I serve as the Senior Technical Adviser/Integrator. The CALFED Program represents what promises to become the world's largest reengineering effort of irrigation systems for environmental restoration and water quality purposes.

In conclusion I want to recognize the following co-authors for their contributions to the papers I have used so liberally: my son Andy Keller whom I have the joy of working collaboratively with; Joe Burns, Grant Davids, Kirk Dimmitt, the team I worked with on verifying water savings for the

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[1] I use reengineering irrigation more or less interchangeably with modernization of irrigation systems.

thrust together development of solutions. Also, in fully closed river basins, the key to effective water management is the ability to implement conservation activities and reallocate water to accommodate changing societal values and manage increasing loads of salts and pollutants. For the most part, we are in the *Conservation* era in the Western United States

To manage a closing water resource systems where irrigation is the major water user during the *Conservation* era requires reengineering irrigation systems that were considered adequate during the *Exploitation* era. This is necessary to improve both the performance and productivity of the system's current water users and uses, and agricultural water use efficiency to conserve and free up water for other users and uses. Thus there are multiple objectives for or benefits of (both local and regional) reengineering (or modernizing) irrigation systems.

Reengineering to conserve water involves changing flow paths in one or more of three general categories - *evaporative depletion flow paths, surface flow paths* and *subsurface flow paths.* Objective-based planning involves targeting specific flow path changes to address explicit benefits that are quantifiable in terms of flow rates and flow timing. To achieve the *Targeted Flow Path Changes* requires both infrastructure and management changes (or actions) that focus on the specific flow paths. This in turn requires developing water balance for the overall system and subsystem water balances for the delivery, field application, drainage, and groundwater subsystems within it to be able to guide and focus these actions.

Developing policies and funding the reengineering of irrigation systems to address both local and external public interests can be a very contentious matter, as has been in the case of the Central Valley of California. In my view the essence of and key to the successful consensus building and negotiations is the use of joint fact-finding for resolving policy issues like agricultural water conservation programs. The essence of the joint fact-finding approach is for the different stakeholders and interest groups to collectively develop and agree on the science and local information background. Then collectively negotiate the policy position based on the jointly developed and accepted science combined with local information.

The CALFED Agricultural Water Use Efficiency Program (Ag WUE) is an ongoing application of the joint fact-finding approach. It involves improving the efficiency of irrigated agriculture throughout the Central Valley of California to provide: cost effective benefits to local users in terms of irrigated agricultural productivity; and regional benefits in the form of environmental restoration and improved water quality and reliability. The objective-based process and incentive-driven nature of Ag WUE are presented.

The CALFED Bay-Delta Program is an unprecedented effort to build a framework for managing California's most precious natural resource: water. Thus far Ag WUE has met with considerable success in bringing agricultural, environmental, and urban stakeholders and regulatory agencies together with an agreed upon policy agenda. This has resulted in its currently being at the stage where funding for implementing a rather massive Ag WUE Program has become generally acceptable to the principal California and Federal decision makers. An overview of the overall CALFED program are some specific details of Ag WUE are outlined in included excerpts from the recently prepared document *California's Water Future: A Framework For Action,* dated 15 June 2000.

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Attachment 10

Roos, M. (1992). "The Findings of Bay-Delta Agricultural Sub-Workgroup #1." Letter including 7 attachments from Maurice Roos (CDWR) to David Beringer (Program Manager Bay-Delta Unit).

STATE OF CALIFORNIA—THE RESOURCES AGENCY PETE WILSON, Governor

DEPARTMENT OF WATER RESOURCES
1416 NINTH STREET, P.O. BOX 942836
CRAMENTO, CA 94236-0001
(6) 653-5791

April 1, 1992

David Beringer, Program Manager
Bay-Delta Unit
State Water Resources Control Board
901 "P" Street
Sacramento, California 95814

Dear Mr. Beringer:

The Findings of Bay-Delta Agricultural Sub-Workgroup #1

The report of Agricultural Sub-Workgroup #1, including a summary of findings, is attached. Also attached are the comments of those members of the sub-workgroup who wished to respond to the Draft Report circulated earlier. Finally, I have, as Chair of the sub-group, attached my response to these comments.

The goal of Agricultural Water Conservation Sub-Workgroup #1 was to identify potential annual water savings in the San Joaquin Valley through increased farm irrigation efficiency within the following constraints:

1. Maintain present level of crop production;

2. Maintain present amount of annual net recharge to ground water in non-saline sink areas;

3. Reduce annual net recharge to ground water in saline sink areas (if possible) by increasing irrigation efficiencies to the maximum reasonable target efficiency for irrigation; and

4. Maintain salt balance in the crop root zone as necessary to maintain present crop productivity.

The Sub-Workgroup agreed that an appropriate average target on-farm irrigation efficiency for the San Joaquin Valley should be 73 percent. The 73 percent is calculated as a Seasonal Application Efficiency (SAE) which is defined as follows:

$$SAE = \frac{ETAW + LR + CP}{AW}$$

Where ETAW is the evapotranspiration of applied water (seasonal ET minus effective precipitation)

CP is water for cultural practices such as frost control (usually small)

AW is water applied on-farm, normally the farm headgate amount. (Tailwater recycled internally is not counted but if tailwater is used on a different field, it is part of that field's applied water.)

The target SAE of 73 percent was also based on the assumption that a realistic average distribution uniformity (DU) for irrigation water applied on-farm was 80 percent. Information provided by experts indicated that 80 percent DU may represent a maximum and that a more realistic average was 70-80 percent.

The average on-farm SAEs in Department Detailed Analysis Units (DAUs) were estimated and compared with the target irrigation efficiency of 73 percent. This comparison resulted in the finding that a net water use savings of only 14,000 acre-feet of water remained conservable in a few DAUs. However, there was debate over the lack of AW data available to calculate the SAEs. Practically all of the crop specific applied water data collected thus far is from the southern San Joaquin Valley and in Westlands Water District. Applied water data for the northern San Joaquin Valley was scant and needed strengthening. Estimates made for the northern San Joaquin Valley were inferred from available data and professional judgment. The Sub-Workgroup had to rely on the judgment of experienced professionals. To collect and analyze sufficient data to add statistical significance to the estimates would have entailed large expenditures of time and money.

Agricultural Sub-Workgroup #1 looked at on-farm water application and efficiencies, developing average values in each DAU. By necessity, an average includes high and low values; there probably is some potential for water savings on less efficient individual farms in DAUs where the average SAE exceeds the desired threshold of 73 percent. The group did not look at other service area aspects, such a potential salvage of conveyance losses in saline sink areas (optimistically estimated at 79,000 acre-feet in the 1987 Central Valley Water Use Study).

There was also some discussion of the need for a modeling approach because of lack of good on-farm AW data in some areas. The Sub-Workgroup decided that a new ground and surface water model developed by Montgomery Engineers for the Department, State

David Beringer
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Board, USBR and Contra Costa Water District is not useful for SWG purposes at this present level of development. However, these agencies should continue to work with the SWRCB, USBR, and CCWD to monitor the model's refinement.

Summaries of Sub-Workgroups #2 and #3 will soon follow. If you have any questions or comments, please contact us at (916) 653-9493 (Craddock) or (916) 653-8366 (Roos).

Sincerely,

Maurice Roos

Maurice Roos
Sub-Workgroup Chairman

Attachment

January 15, 1992

Agricultural Water Conservation Sub-Work Group 1
Summary of Findings

This Sub-Work Group was concerned with 1985 level unit water use and irrigation efficiencies in the San Joaquin Valley, especially in the Delta export service area. Crop water use factors included irrigated acreage, unit applied water use (AW), unit evapotranspiration (ET) and unit evapotranspiration of applied water (ETAW). The task included examining available crop water use data, providing judgments on reasonable uses and "target" efficiencies, and estimating how much new water would be made available by improved water management in the San Joaquin Valley agricultural sector. This was a general overview; areas of shallow ground water and the San Joaquin basin west side drainage question were set aside for more intensive studies by Sub-Work Groups 2 and 3.

It is recognized that the major share of recharge to San Joaquin Valley ground water basins is derived from the portion of applied irrigation water which percolates beyond the rooting zone of crops. Thus, the excess percolation water is not lost but becomes ground water and river accretion, which is available for reuse. Only in some areas, primarily on the west side, is the deep percolation degraded beyond general usability by excessive salts either in the soil or in shallow saline ground water bodies. In these "salt sink" areas, deep percolation represents a loss of potentially usable water from the system.

Attachment 11

Willardson, L. S. (1959). "Characterizing Water Use By Means Of Efficiency Concepts." Paper presented at 1959 Annual Meeting of American Society of Agricultural Engineers, Ithaca, New York.

CHARACTERIZING WATER USE BY MEANS OF EFFICIENCY CONCEPTS 1/

by
Lyman S. Willardson 2/

Introduction

Efficiency is a term which has important application in almost all forms of human endeavor. When resources are plentiful, for example, efficiency in their use has little immediate significance. When resources are scarce, efficiency may be a matter of economic life or death. This same statement applies to the use of water. Where there is plenty and little competition for it, efficiency of use has little economic importance. At present, however, economic competition plus the increasing number of water users and water uses has brought forcibly to our attention that water is a limited and valuable resource. Economic competition daily reduces the supply of water available for agriculture. It also is reducing the profit margin on farms and requiring more efficient crop production through better farming methods, including better irrigation.

If irrigation is to be efficient, then we must have specific terms to define what irrigation is supposed to do. The irrigation definitions we are using at present are necessary but not sufficient. There is a need to be more definitive.

History

The concept of the relation of irrigation water used to land area served, or the idea "irrigation efficiency" has evolved as a matter of necessity. The rate of evolution has been determined to some degree by organized research. An early expression of the concept was the term, "duty of water," mentioned by Dr. J. A. Widstoe (3) in 1914. 1/ This term "duty of water" was used as a measure of the area of land that would be served by a given unit of water. It is a useful term and might better be spoken of as, "water allotment." It defines the amount of water that must be provided to an area to meet the consumptive use needs of the crops and to provide the extra water which will be needed for leaching or which will be lost in canals and on farms due to local peculiarities of soil, water, and irrigation practice. It is an expression of the practical water needs of land.

As knowledge of irrigation and water control methods increased, a finer differentiation of water use and loss was necessary. New

1/ Presentation at the ASAE Annual Summer Meeting, Cornell University, Ithaca, New York, June 22, 1959.

2/ Agricultural Engineer, Western Soil and Water Management Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, Logan, Utah.